UiO : Faculty of Mathematics and Natural Sciences
University of Oslo

Department of Informatics
Networks and Distributed Systems (ND) group

INF 3190
Wireless Communications

Özgü Alay
ozgu@simula.no
Simula Research Laboratory

Outline

- Brief history of wireless
- What is wireless communication?
- Bottom-down approach
  - Physical layer : how can we transmit signals in air?
  - Link layer : multiple access
  - Wireless impact higher layers?
- Wireless Systems
  - Mobile Broadband Networks
  - Wifi
  - Sensor Networks, Adhoc Networks

Wireless History

- James C Maxwell (1831- 1879) laying the theoretical foundation for EM fields with his famous equations
- Heinrich Hertz (1857- 1894) was the first to demonstrate the wave character of electrical transmission through space (**1886**). (Note Today the unit Hz reminds us of this discovery).
- Radio invented in the **1880s** by Marconi
- The 1st radio broadcast took place in **1906** when Reginald A Fessenden transmitted voice and music for Christmas.
- The invention of electronic vacuum tube in **1906** by Lee De Forest (1873-1961) & Robert Von Lieben (1878 – 1913) helped to reduce the size of sender and receiver .

Wireless History cont…

- In **1915** , the first wireless voice transmission was set up between New York and San Francisco
- The 1st commercial radio station started in **1920**
  - Note Sender & Receiver still needed huge antennas due to high transmission power.
- In **1926**, the first telephone in a train was available on the Berlin – Hamburg line
- **1928** was the year of many field trials for TV broadcasting. John L Baird (1888 – 1946) transmitted TV across Atlantic and demonstrated color TV

Wireless History cont …

- Invention of FM in 1933 by Edwin H Armstrong [1890 - 1954] .
- 1946, Public Mobile in 25 US cities, high power transmitter on large tower. Covers distance of 50 Km. Push to talk.
- After 2nd world war (in 1958), a network in Germany was build namely the analog A- Netz using a carrier frequency of 160 Mhz.
  - Connection setup was only possible from the mobile station and no handover was possible

Wireless History cont …

- 1982: ***Groupe Spéciale Mobile*** was launched to develop standards for pan-European mobile network
- GSM now stands for ***Global System for Mobile Communications***
- 1992 Official commercial launch of GSM in Europe
- 1997 - Wireless LANs
- 2000 - Bluetooth with 1Mbit/s specification, single cell. Later work on 10Mbit/s spec with multi cell capability
- In 2002 Camera phones are first introduced in the U.S. market.

Wireless History cont …

- In 2005 mobile phone subscribers exceed fixed phone subscriber.
- iTunes Application Store (July) and Android Market (October) open in 2008
- In 2012 the number of subscriber reaches 1 million.
- In 2014, the number of mobile devices grow to a total of 7.4 billion, exceeding the world's population.

- 2016: 5G, convergence of technologies to support billions of connected devices.

Outline

- Brief history of wireless
- What is wireless communication?
- Bottom-down approach
  - Physical layer : how can we transmit signals in air?
  - Link layer : multiple access
  - Wireless impact higher layers?
- Wireless Systems
  - Mobile Broadband Networks
  - Wifi
  - Sensor Networks, Adhoc Networks

Why Wireless?

- Freedom from wires
  - No cost of installing the wires
  - Not deal with bunches of wires running around
- Global coverage
  - where wired communication is not feasible or costly e.g. rural areas, battle field and outer space.
- Stay Connected
  - Any where any time, even under mobility
- Flexibility
  - Connect to multiple devices simultaneously

What is Wireless Communication?

- Transmitting voice and data using electromagnetic waves in open space
- Electromagnetic waves
  - Travel at speed of light ($c = 3x10^8$ m/s)
  - Has a frequency (f) and wavelength (λ)
    - » $c = f \times \lambda$

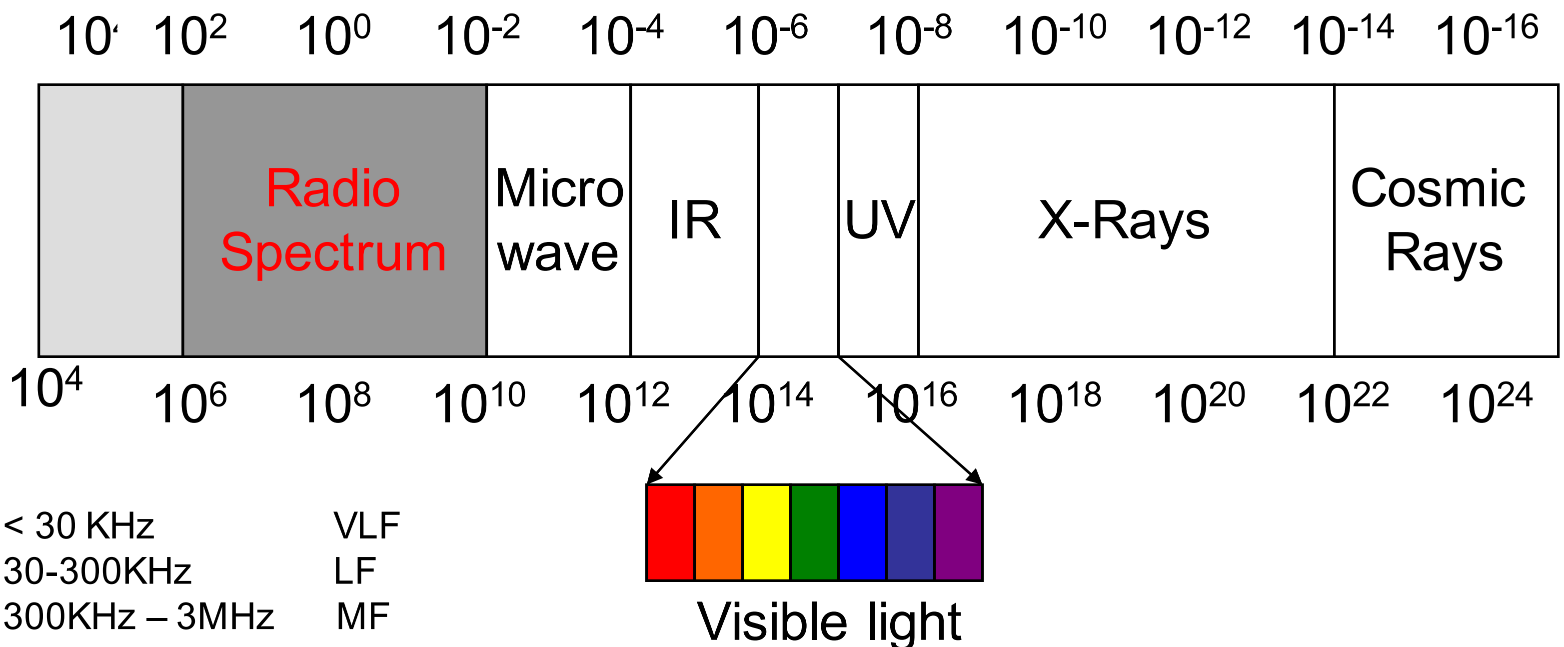
Wireless Link Characteristics

- *decreased signal strength:* radio signal attenuates (lose signal strength) as it propagates through matter (path loss)
  - Higher frequencies will attenuate FASTER
  - Higher frequencies also don't penetrate objects as well
- *interference from other sources:* standardized wireless frequencies shared by other devices (e.g., phone); devices (motors) interfere as well
- *multipath propagation:* radio signal reflects off objects/ground, reaching destination at slightly different times

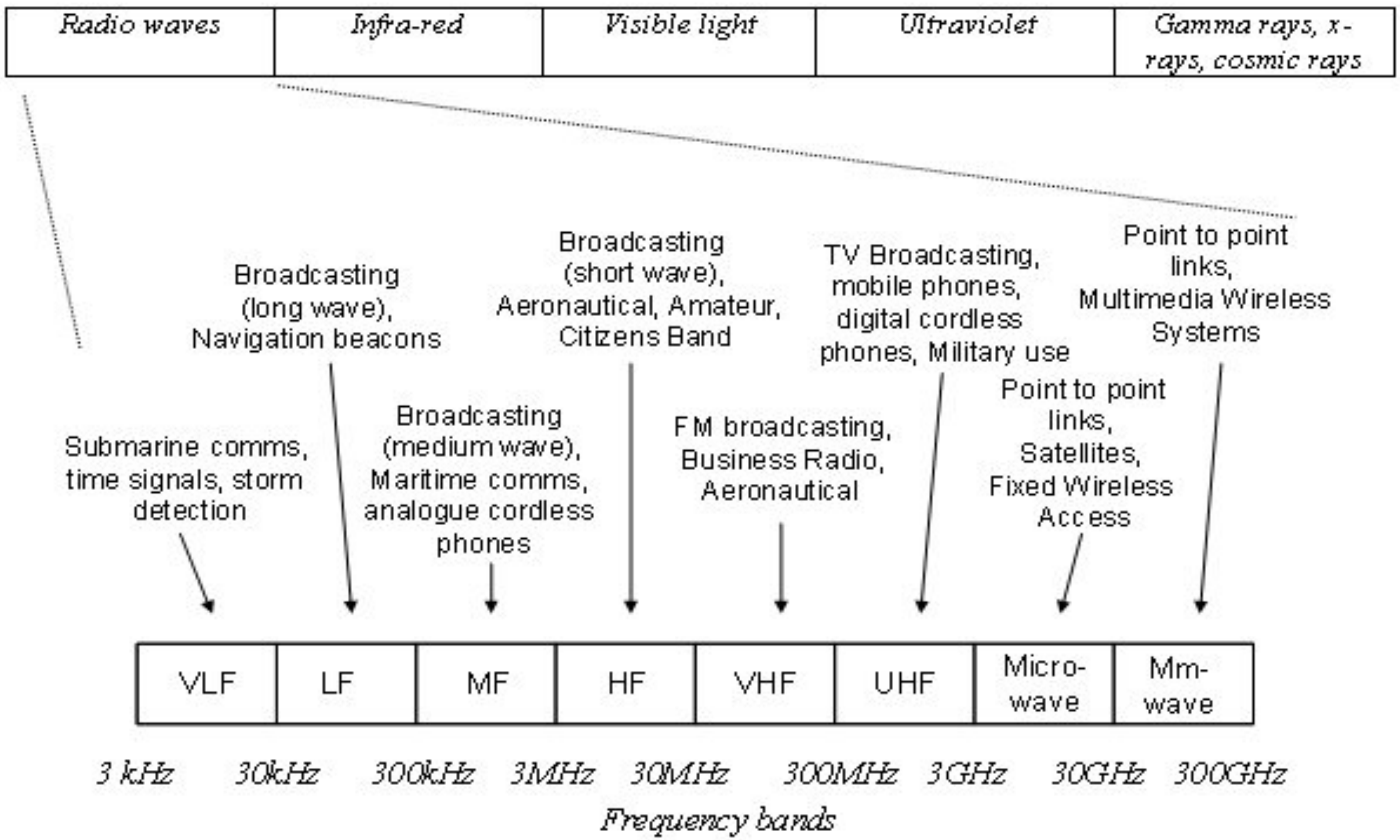
…. make communication across (even a point to point) wireless link much more "difficult"

Electromagnetic Spectrum

1MHz ==100m
100MHz ==1m
10GHz ==1cm



< 30 KHz	VLF
30-300KHz	LF
300KHz – 3MHz	MF
3 MHz – 30MHz	HF
30MHz – 300MHz	VHF
300 MHz – 3GHz	UHF
3-30GHz	SHF
> 30 GHz	EHF

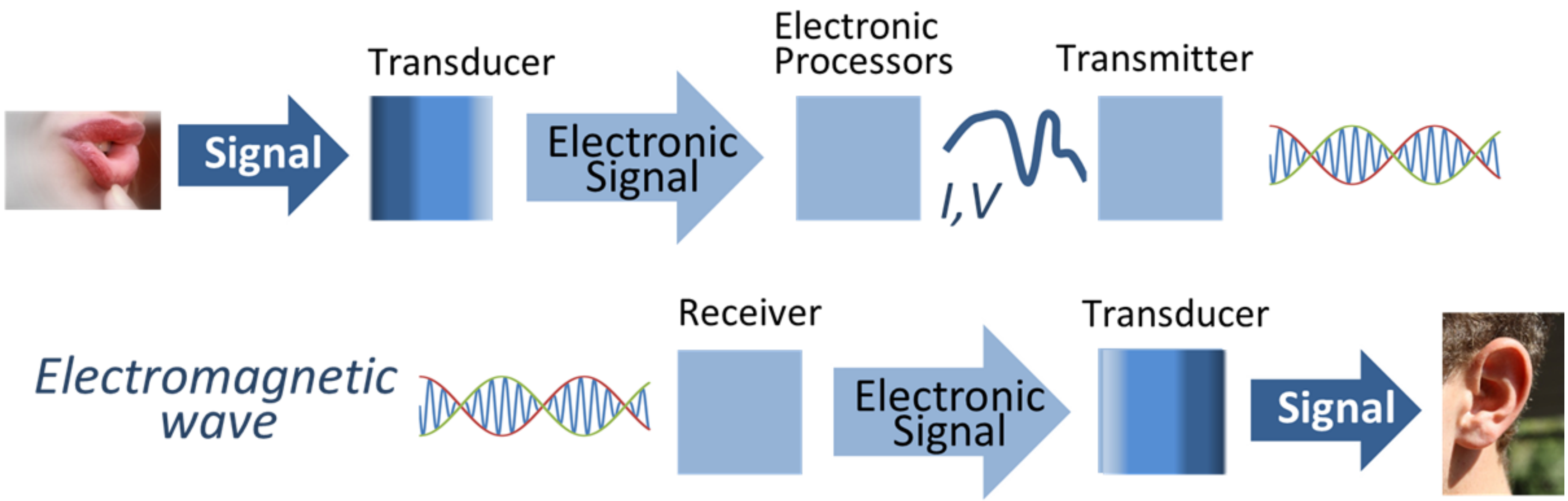

Radio waves
Infra-red
Visible light
Ultraviolet
Gamma rays, x-rays, cosmic rays
Broadcasting (long wave), Navigation beacons
Broadcasting (short wave), Aeronautical, Amateur, Citizens Band
TV Broadcasting, mobile phones, digital cordless phones, Military use
Point to point links, Multimedia Wireless Systems
Submarine comms, time signals, storm detection
Broadcasting (medium wave), Maritime comms, analogue cordless phones
FM broadcasting, Business Radio, Aeronautical
Point to point links, Satellites, Fixed Wireless Access
VLF
LF
MF
HF
VHF
UHF
Micro-wave
Mm-wave
3 kHz
30kHz
300kHz
3MHz
30MHz
300MHz
3GHz
30GHz
300GHz
Frequency bands

Outline

- Brief history of wireless
- What is wireless communication?
- Bottom-down approach
  - Physical layer : how can we transmit signals in air?
  - Link layer : multiple access
  - Wireless impact higher layers?
- Wireless Systems
  - Mobile Broadband Networks
  - Wifi
  - Sensor Networks, Adhoc Networks

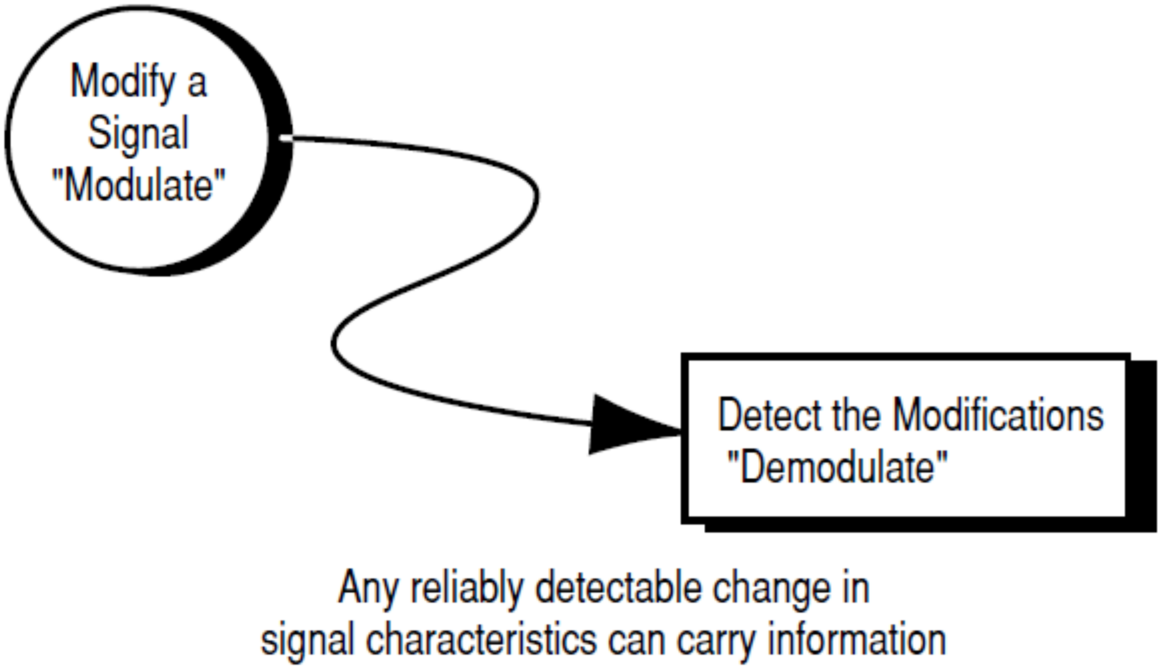
Block diagram of radio transmission

- Information (e.g. sound) is converted by a transducer (e.g. a microphone) to an electrical signal
- This signal is used to modulate a radio wave sent from a transmitter.
- A receiver intercepts the radio wave and extracts the information-bearing electronic signal, which is converted back using another transducer such as a speaker.



What is modulation?

- Modulation = Adding information to a carrier signal
- The sine wave on which the characteristics of the information signal are modulated is called a carrier signal

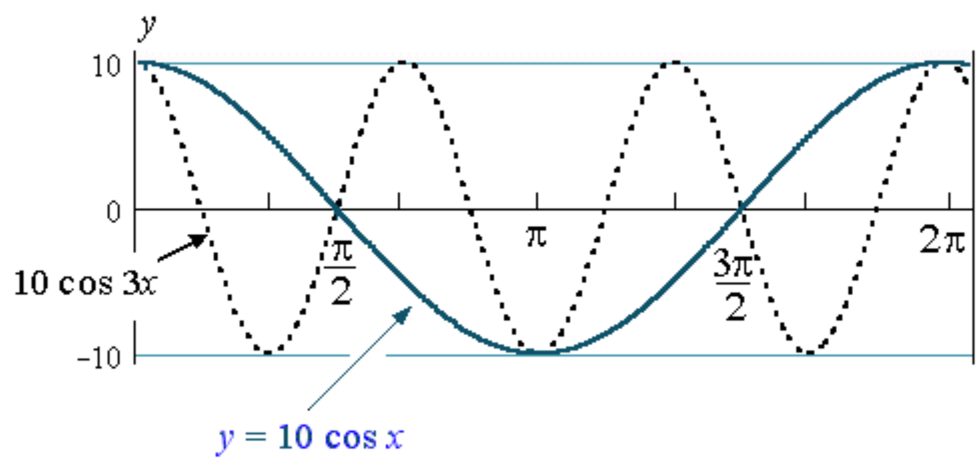


Preliminaries

Carrier signal:

- $A \cos (2\pi f_C t + \varphi)$

Amplitude — Frequency — Phase

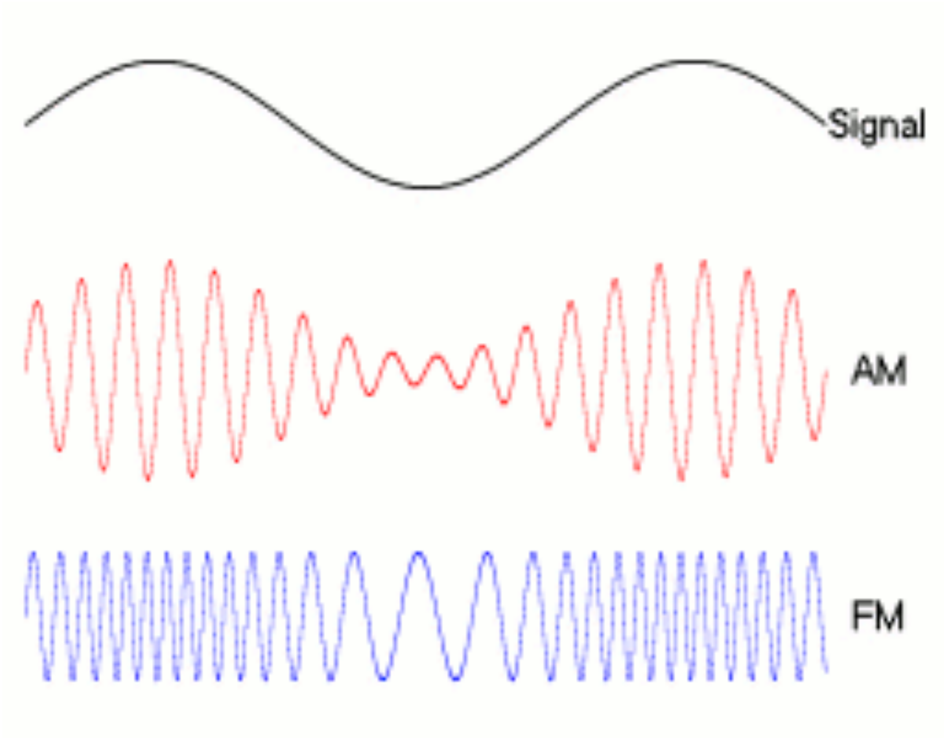


Types of Modulation

- ANALOG MODULATION: If the variation in the parameter of the carrier is continuous in accordance to the input analog signal the modulation technique is termed as analog modulation scheme

- DIGITAL MODULATION: If the variation in the parameter of the carrier is discrete then it is termed as digital modulation technique

ANALOG MODULATION

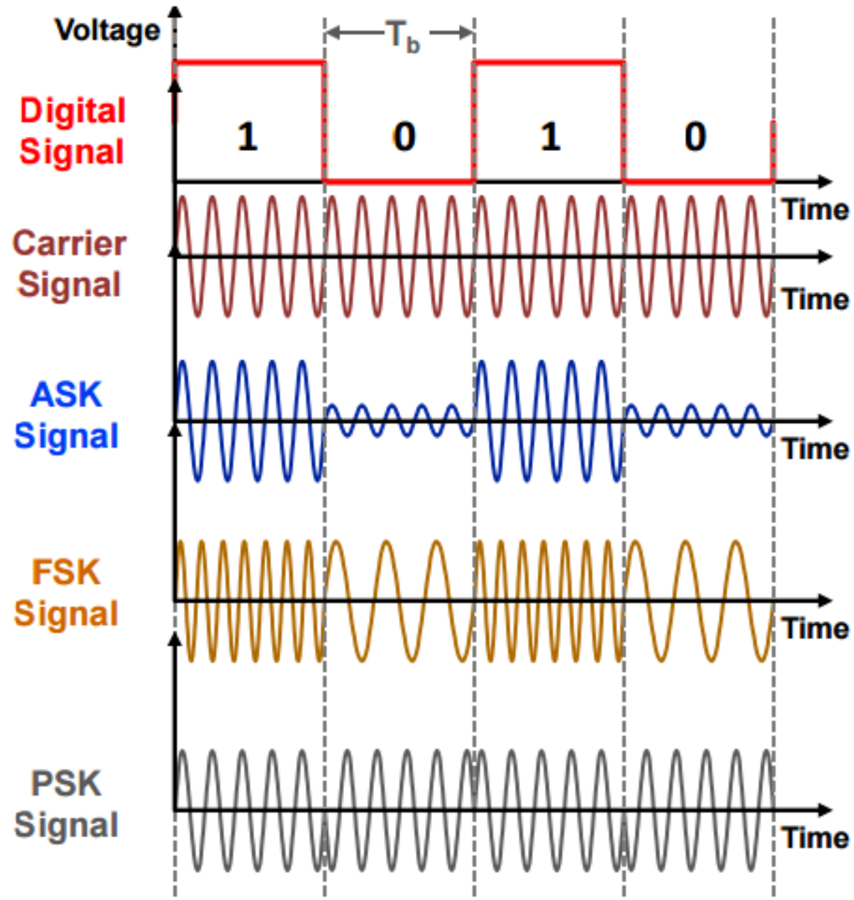


Amplitude Modulation:
Signal shapes the amplitude of the carrier

Frequency Modulation:
Signal shapes the frequency of the carrier

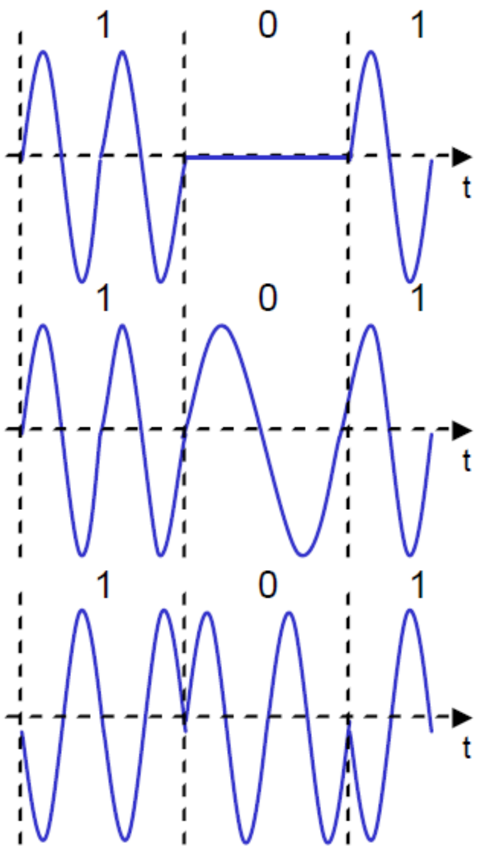
DIGITAL MODULATION TECHNIQUES

1. **Baseband digital message signal**: $m(t)$
2. **Analog sinusoidal carrier signal**:
   A. Carrier signal: $A_c \cos(2\pi f_c t + \phi_c)$
3. **ASK: Amplitude Shift Keying**.
   A. Message signal changes the carrier's **amplitude** : $A_i(t)$.
4. **FSK: Frequency Shift Keying**.
   A. Message signal changes the carrier's **frequency** : $f_i(t)$.
5. **PSK: Phase Shift Keying.**
   A. Message signal changes the carrier's **phase** : $\phi_i(t)$.



Digital modulation techniques comparison

- Amplitude Shift Keying (ASK):
  - change amplitude with each symbol – frequency constant
  - low bandwidth requirements
  - very susceptible to interference
- Frequency Shift Keying (FSK):
  - change frequency with each symbol
  - needs larger bandwidth
- Phase Shift Keying (PSK):
  - Change phase with each symbol
  - More complex
  - robust against interference

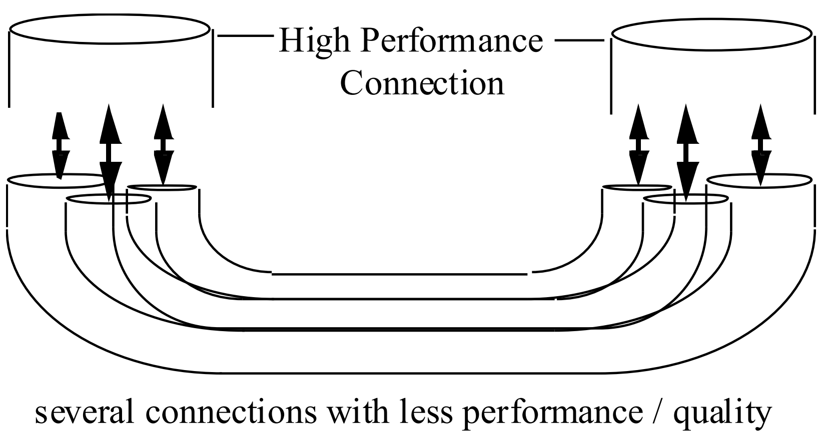


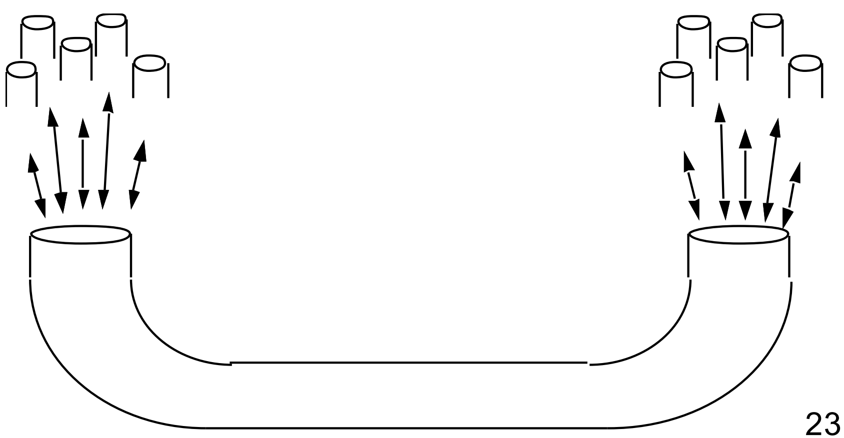
Outline

- Brief history of wireless
- What is wireless communication?
- Bottom-down approach
  - Physical layer : how can we transmit signals in air?
  - Link layer : multiple access
  - Wireless impact higher layers?
- Wireless Systems
  - Mobile Broadband Networks
  - Wifi
  - Sensor Networks, Adhoc Networks

Multiplexing (MUX) / Multiple Access (MA)

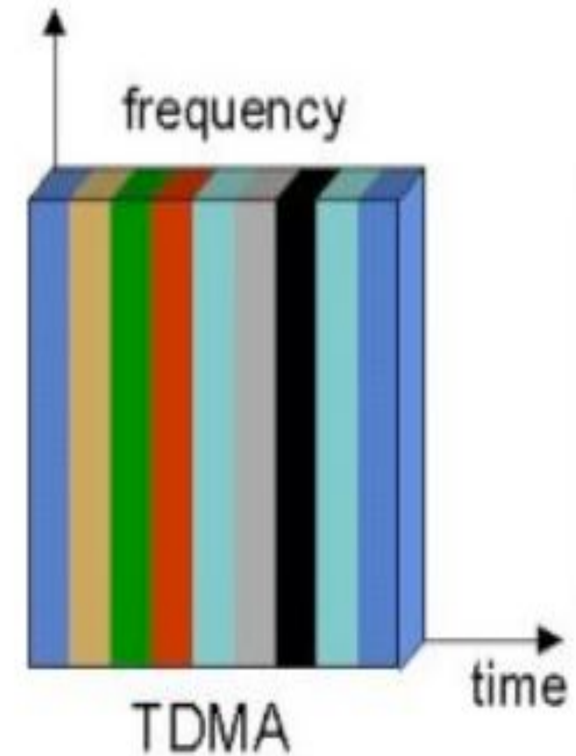
- Transmission of several data flows (logical connections) over one medium
  - Realize individual "connections", *normally* with deterministic properties (throughput, delay)
  - Terminology: ??M („".. Multiplexing") or ??MA (".. Multiple Access")
- Also:
  Transmission of one data flow (logical connection) over several media
  - (increase performance and/or reliability)





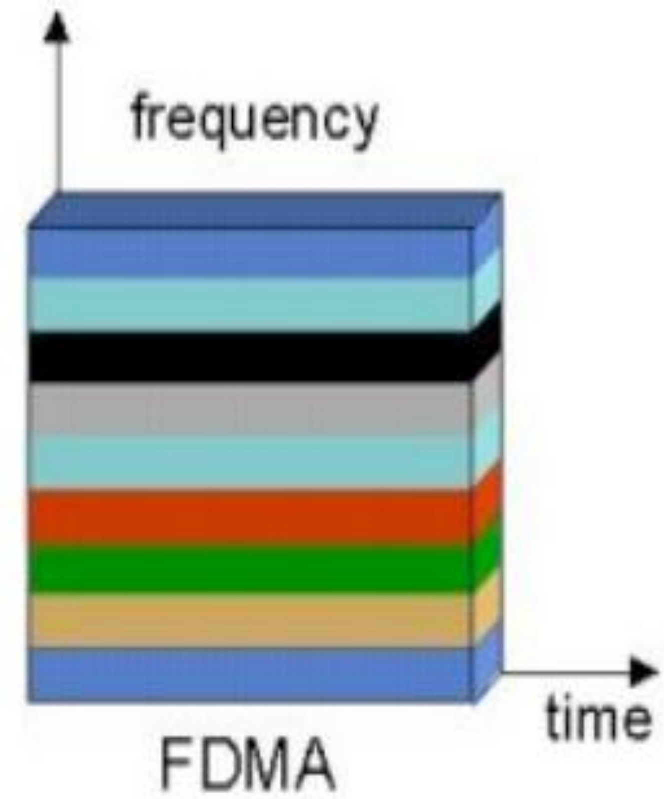
Time Division Multiple Access (TDMA)

- Each user is allowed to transmit only within specified time intervals (Time Slots). Different users transmit in different Time Slots.
- When users transmit, they occupy the whole frequency bandwidth (separation among users is performed in the time domain).
- Commonly used in GSM together with frequency hopping



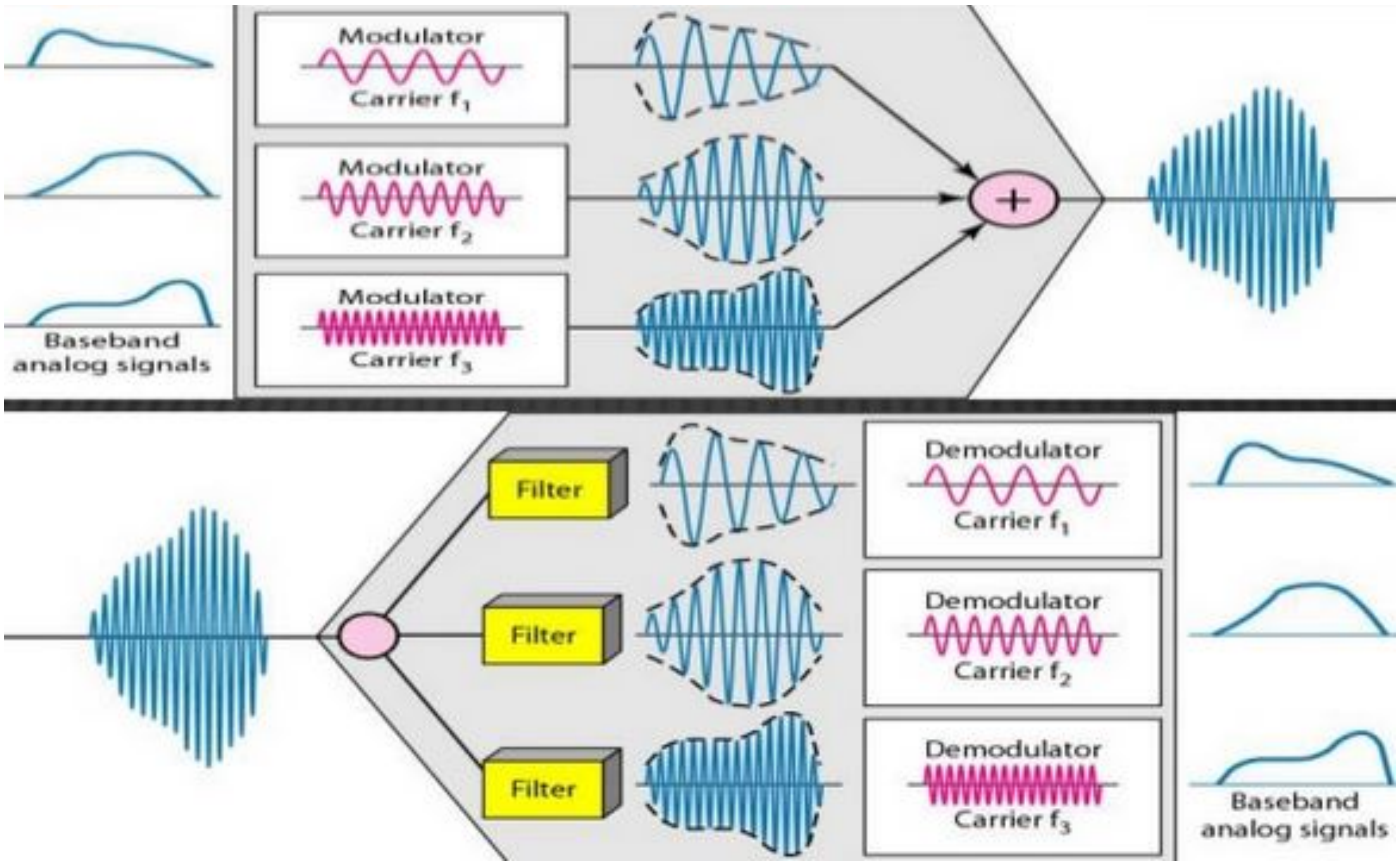
Frequency Division Multiple Access (FDMA)

- Each user transmits with no limitations in time, but using only a portion of the whole available frequency bandwidth
- Different users are separated in the frequency domain
- FDMA can be used for both digital and analog signals
- Very common in satellite communications



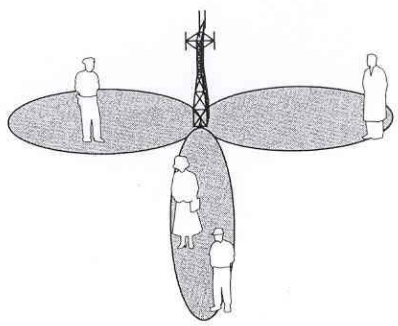
❑ The major disadvantage of FDMA is the relatively expensive and complicated bandpass filters required.

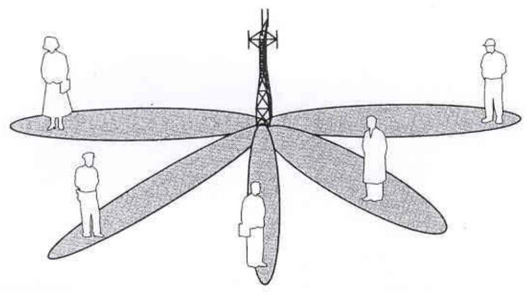
FDMA in time domain



Space Division Multiple Access

- Controls radiated energy for each user in space using spot beam antennas
- Base station tracks user when moving
- Primitive applications are "Sectorized antennas"
- Adaptive antennas can simultaneously steer energy in the direction of many users at once
- Considered as an option for 5G

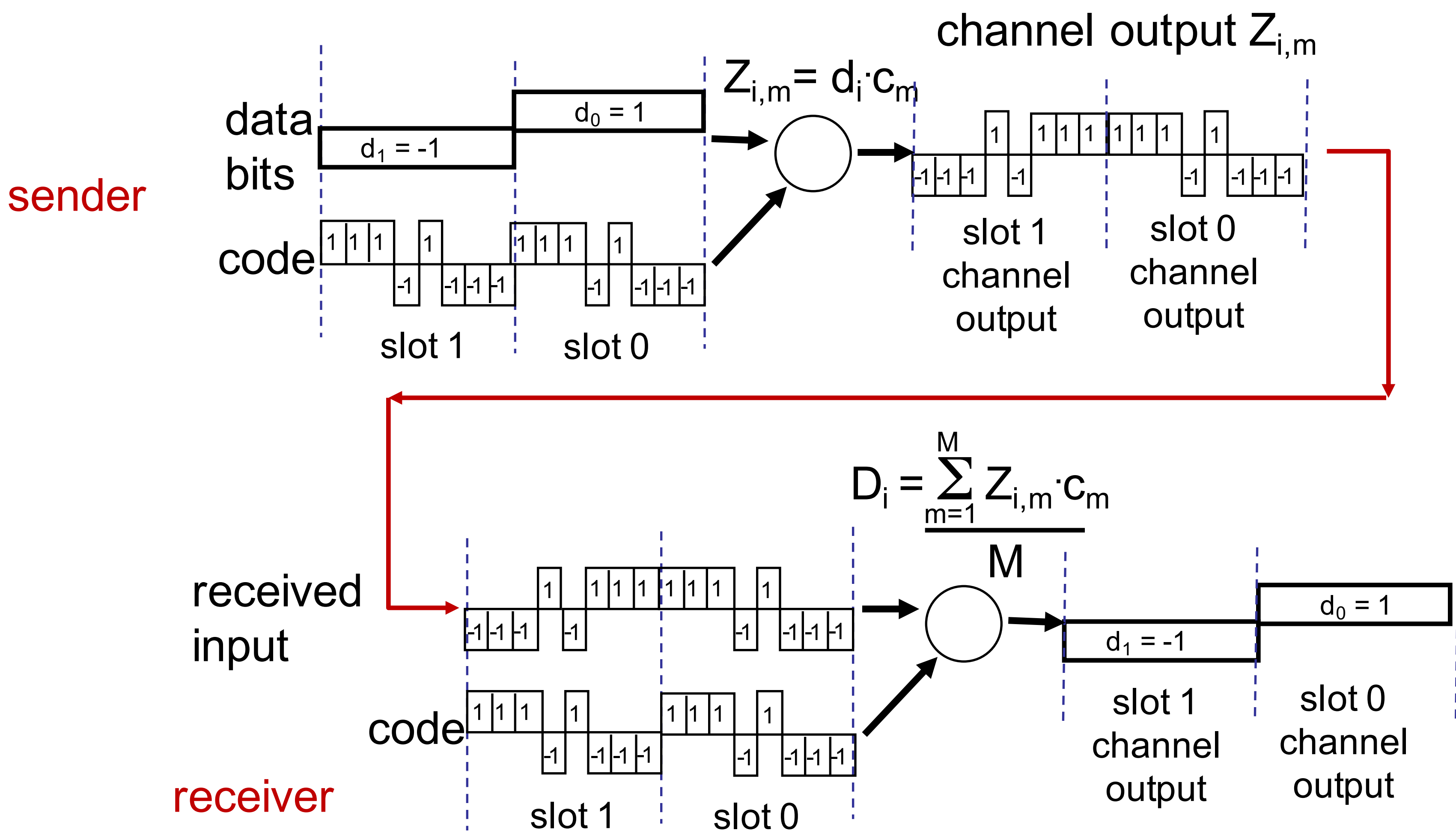




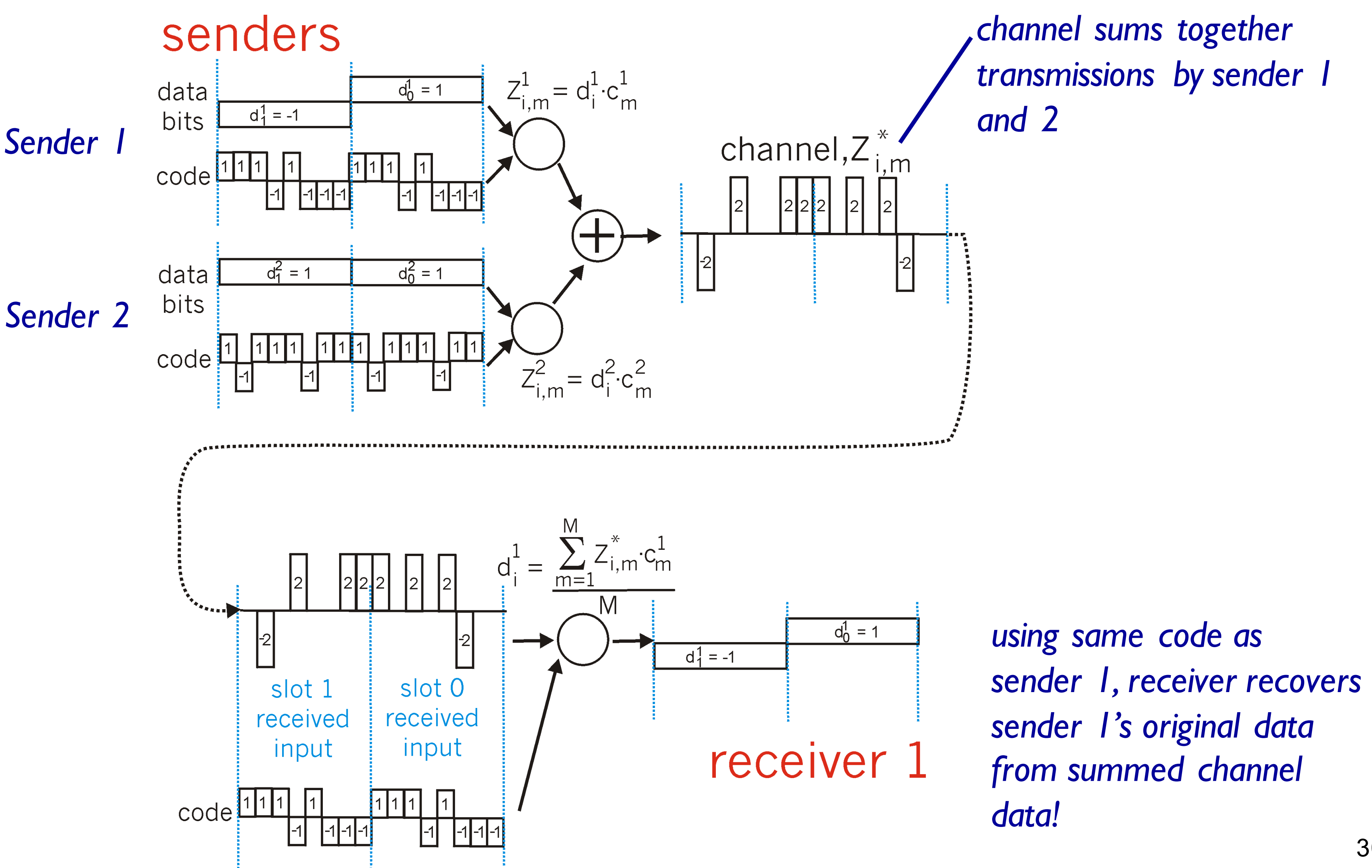
Code Division Multiple Access (CDMA)

- unique "code" assigned to each user; i.e., code set partitioning
  - all users share same frequency, but each user has own "chipping" sequence (i.e., code) to encode data
  - allows multiple users to "coexist" and transmit simultaneously with minimal interference
- Chip sequences are orthogonal to ensure reconstructability:
  - seq. 1: $x = (x_1, .. x_n)$, seq. 2: $y = (y_1, .. y_n)$ $\sum x_i y_i = 0$
  - Common choice: Walsh sequence
- *encoded signal* = (original data) X (chipping sequence)
- *decoding:* inner-product of encoded signal and chipping sequence

CDMA encode/decode

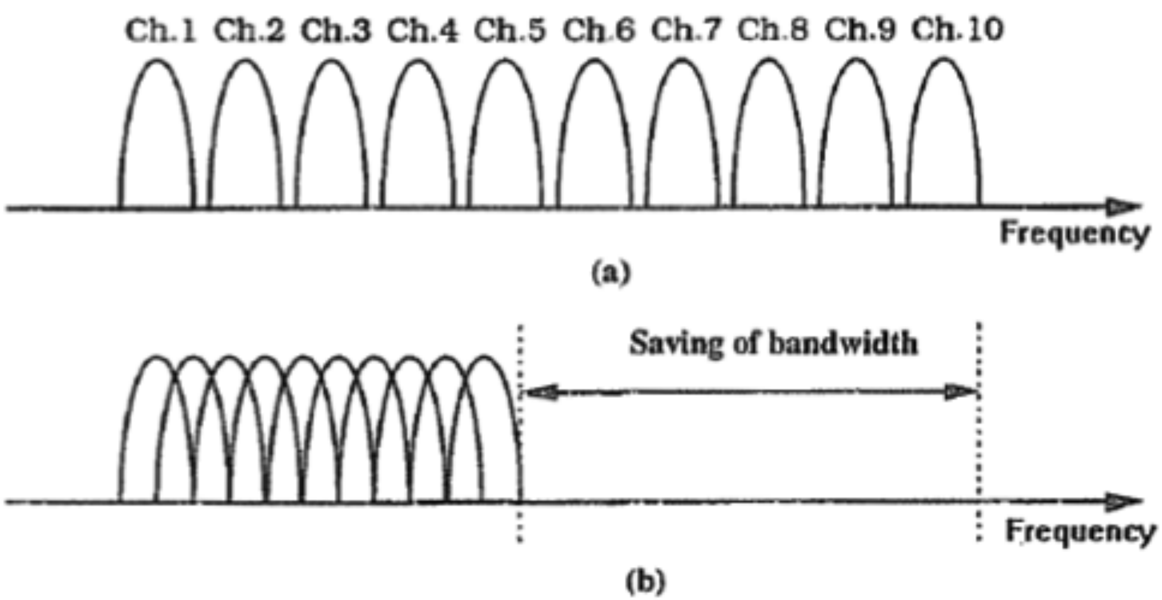


CDMA: two-sender interference



Orthogonal Frequency Division Multiple Access (OFDMA)

- The carriers are chosen such that they are orthogonal to one another



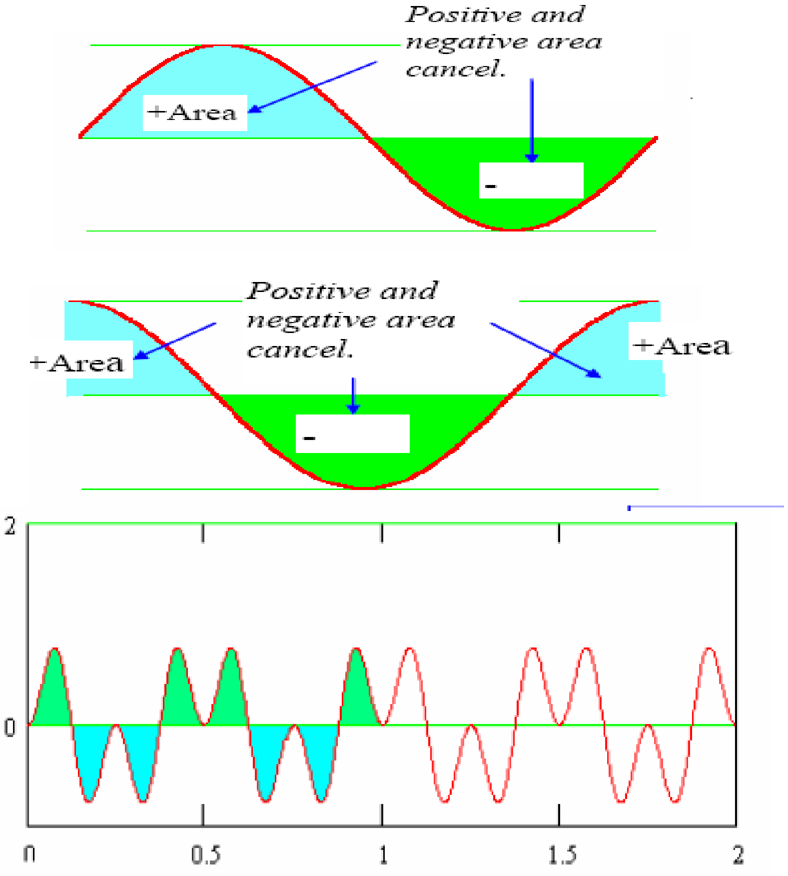
Conventional multicarrier

Orthogonal multicarrier

Orthogonality Principle

- Real Function space

$$f_1(t) = A\sin(wt)$$
$$f_2(t) = B\cos(wt)$$
$$\int_{\tau}^{\tau+T} f_1(t) f_2(t)\,dt = 0$$
$$f_m(t) = M\sin(mwt)$$
$$f_n(t) = N\cos(nwt)$$
$$\int_{\tau}^{\tau+T} f_m(t) f_n(t)\,dt = 0$$

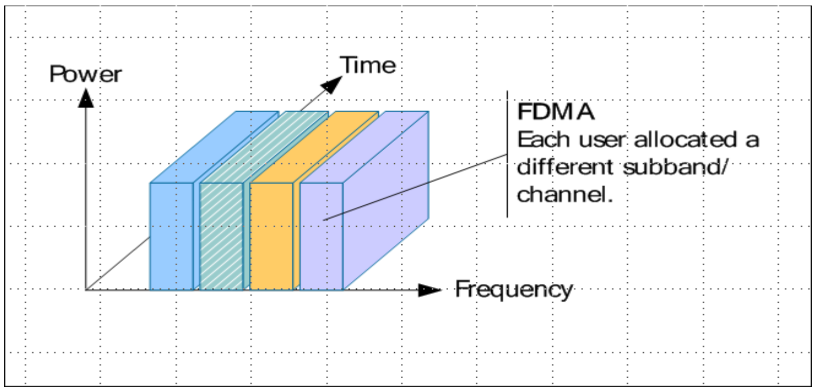


$$f(t) = \sin(wt)\sin(2wt)$$

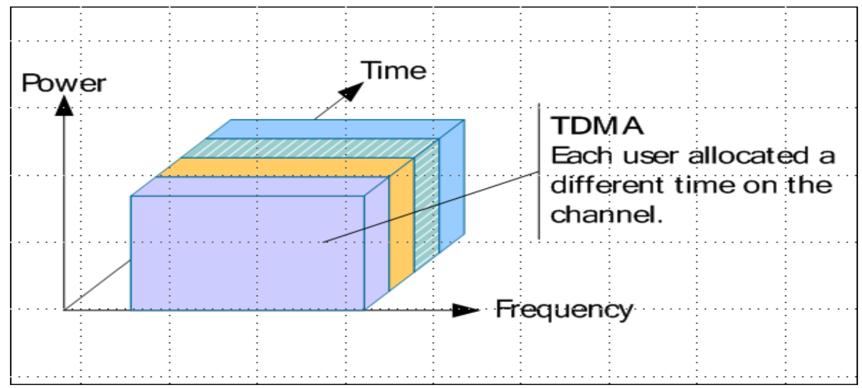
Here *mw* and *nw* are called *m-th* and *n-th* harmonics of *w respectively*

Summary: FDMA,TDMA, CDMA and OFDMA

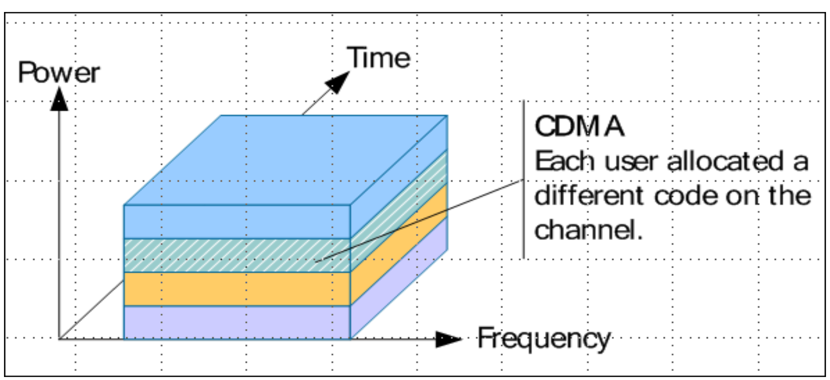
1G/TACS



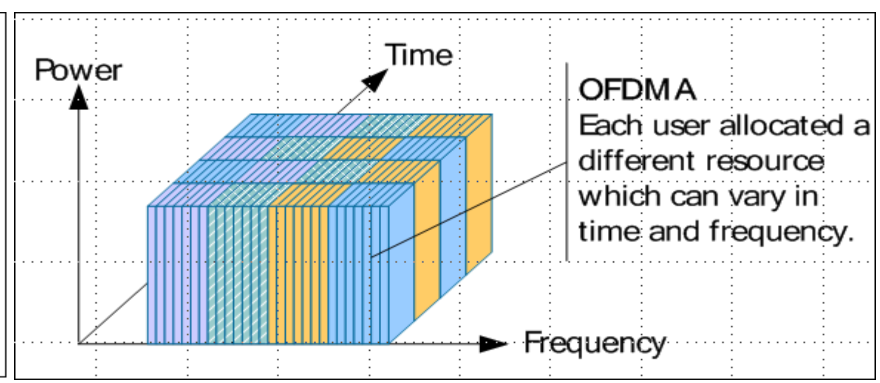
2G/GSM



3G



4G/LTE and Wimax



Outline

- Brief history of wireless
- What is wireless communication?
- Bottom-down approach
  - Physical layer : how can we transmit signals in air?
  - Link layer : multiple access
  - Wireless impact higher layers?
- Wireless Systems
  - Mobile Broadband Networks
  - Wifi
  - Sensor Networks, Adhoc Networks

Wireless: impact on higher layers

- logically, impact *should* be minimal …
  - best effort service model remains unchanged
  - TCP and UDP can (and do) run over wireless, mobile
- … but performance-wise:
  - packet loss/delay due to bit-errors (discarded packets, delays for link-layer retransmissions), and handoff
  - TCP interprets loss as congestion, will decrease congestion window un-necessarily
  - delay impairments for real-time traffic
  - limited bandwidth of wireless links

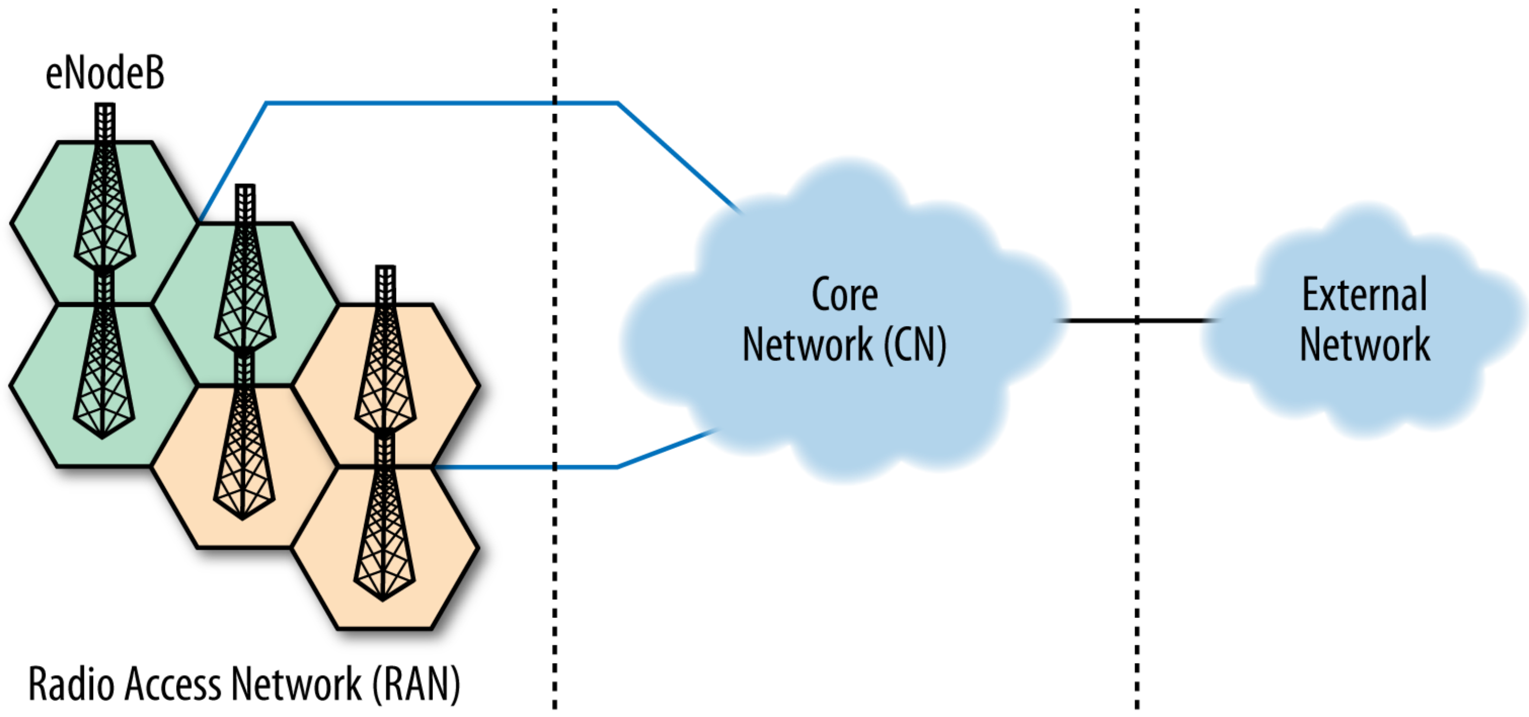
Outline

- Brief history of wireless
- What is wireless communication?
- Bottom-down approach
  - Physical layer : how can we transmit signals in air?
  - Link layer : multiple access
  - Wireless impact higher layers?
- Wireless Systems
  - Mobile Broadband Networks
  - Wifi
  - Sensor Networks, Adhoc Networks

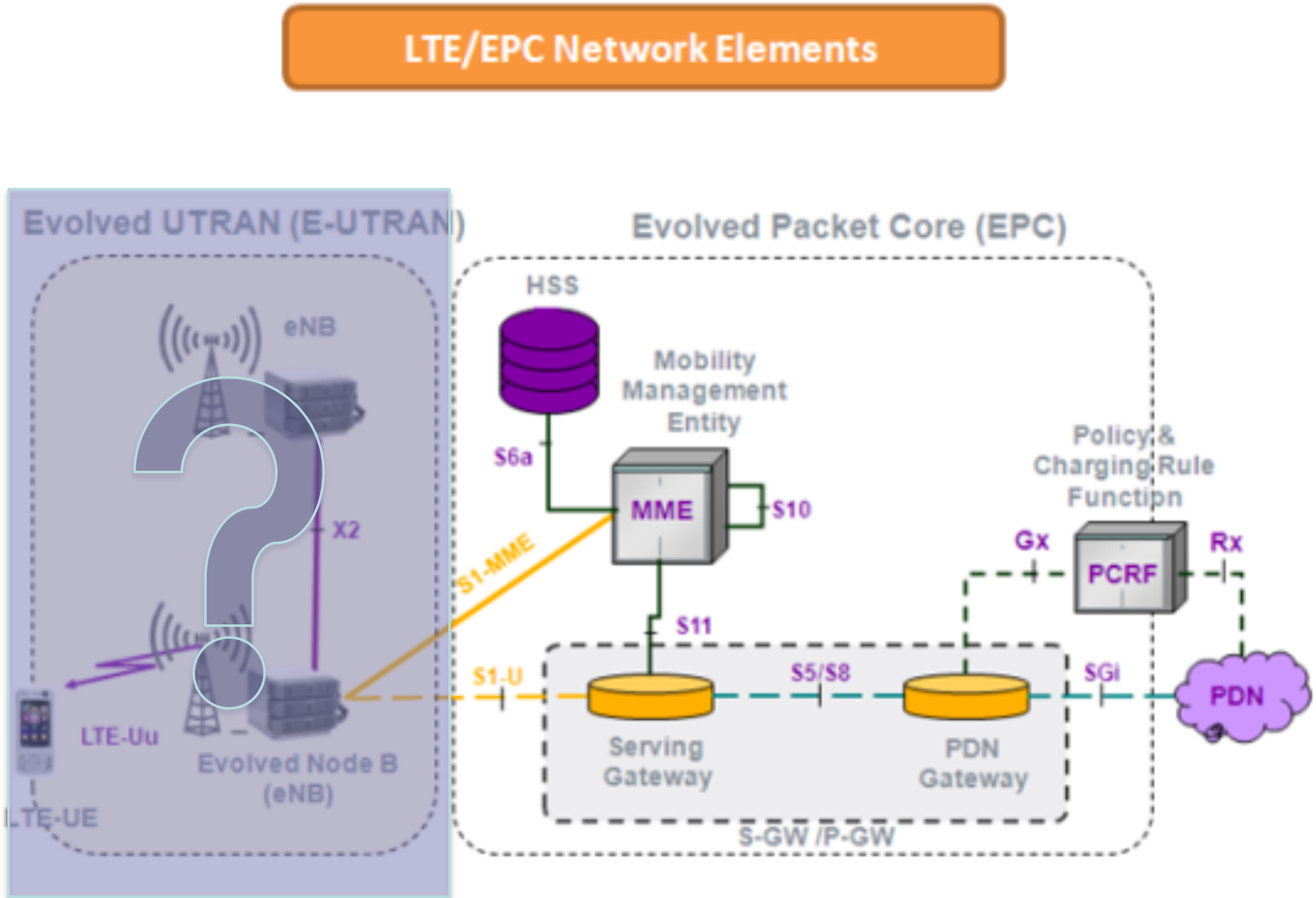
Mobile Broadband (MBB) Networks

- Building Blocks of MBB Networks
  - Radio Access Network
  - Core Network

Macro View


eNodeB
Core
Network (CN)
External
Network
Radio Access Network (RAN)

Closer look to LTE

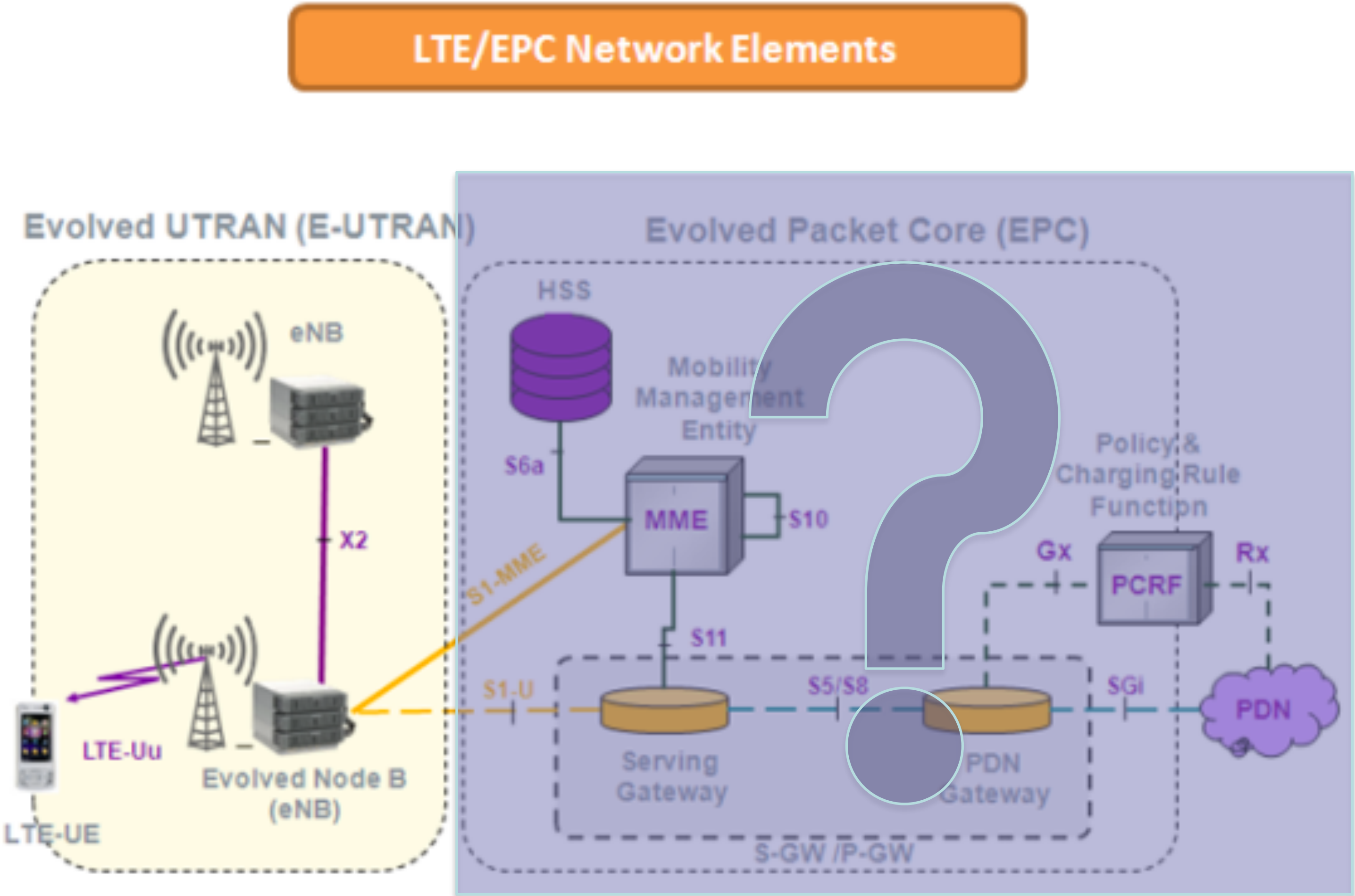


UTRAN: UMTS Terrestrial Radio Access Network

eNodeB

- Handover management
  - If target eNodeB is known and reachable -> eNodeBs communicate (neighbor relations through mobile devices)
  - If not, over the core network
- Inter-cell interference coordination
  - Mobile devices report noise levels to their serving eNodeB
  - Contact with neighboring eNodeB to mitigate the problem
- Dynamic Air Interface Resource Allocation (Scheduler)

Closer look to LTE



Packet Data Network Gateway (PDN-GW)

- Point of contact with the outside world
  - Connectivity between the UE to external packet data networks
  - point of exit and entry of traffic for the UE
- The PDN GW performs policy enforcement, packet filtering for each user, charging support, lawful Interception and packet screening.

Serving Gateway (S-GW)

- Acts like a high level router
  - Routes and forwards user data packets from eNodeBs to PDN-GW
- Mobility anchor for the user plane during inter-eNB handovers
- Anchor for mobility between LTE and other 3GPP technologies

Mobility Management Entity (MME)

- **Network Access Control**: MME manages authentication and authorization for the UE.
- **Radio Resource Management**: MME works with the HSS and the RAN to decide the appropriate radio resource management strategy (RRM) that can be UE-specific.
- **Mobility Management**: One of the most complex functions MME performs. Providing seamless inter-working has multiple use cases such as Inter-eNB and Inter-RAT, among others.

Mobility Management Entity (MME)

- **Roaming Management**: MME supports outbound and inbound roaming subscribers from other LTE/EPC systems and legacy networks.
- **UE Reachability**: MME manages communication with the UE and HSS to provide UE reachability and activity-related information.
- **Lawful Intercept**: Since MME manages the control plane of the network, MME can provide the whereabouts of a UE to a law enforcement monitoring facility.

Home Subscriber Service (HSS)

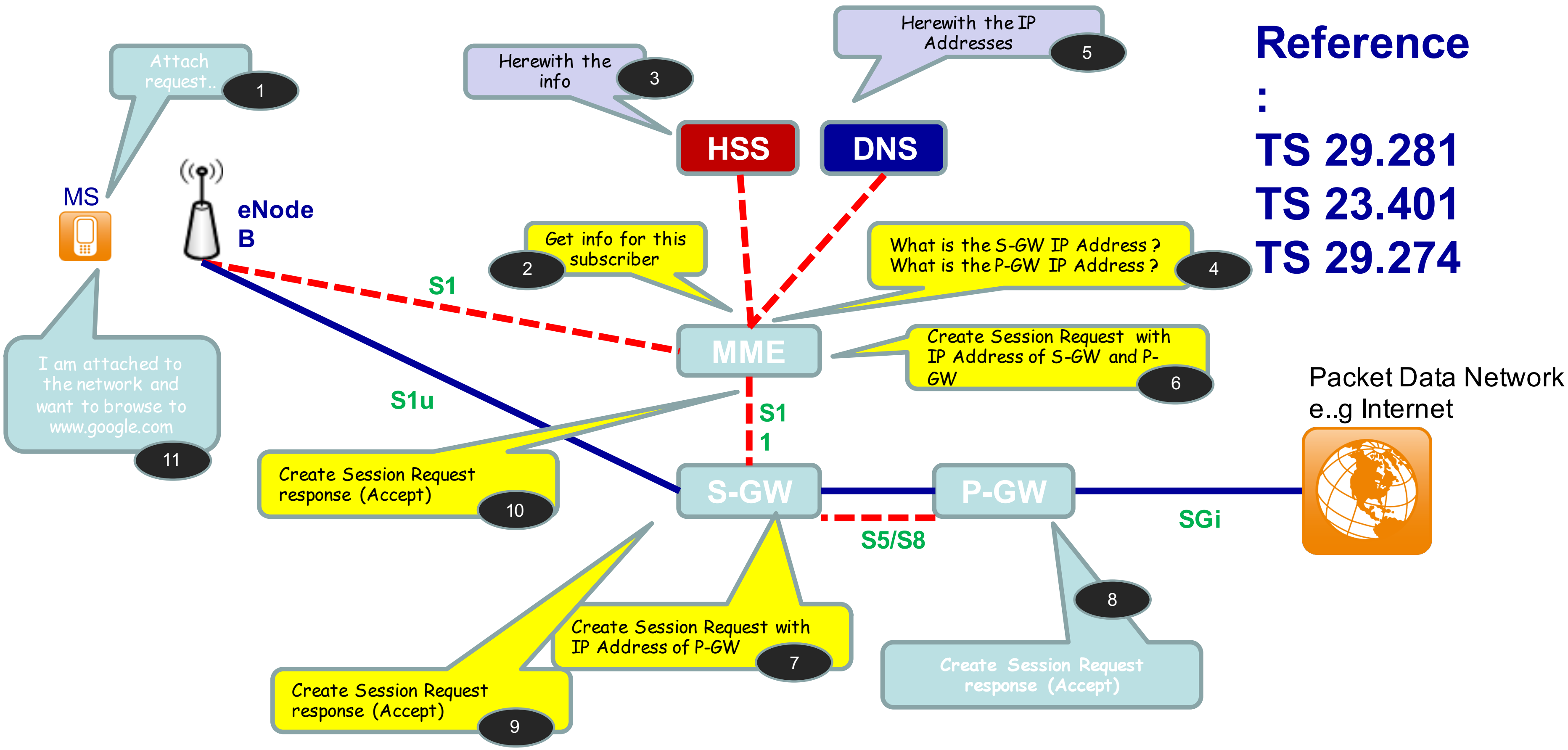
- Central database that contains information about all the network operators subscribers
- Contains the subscription related information (subscriber profiles)
- Performs authentication and authorization of the user
- Provides information about the subscriber's location and IP

Policy and Charging Rule Function (PCRF)

How a certain packet is delivered to a certain user considering the QoS and charging?

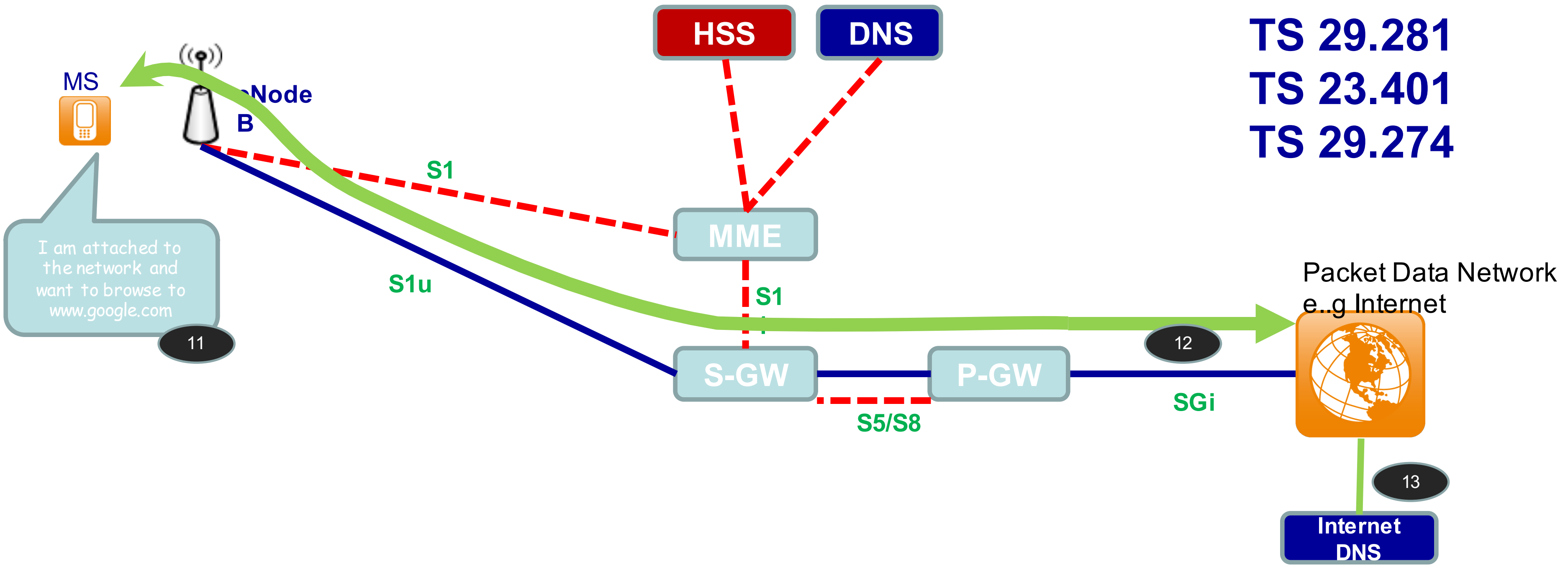
- QoS: Differentiation of subscribers and services
- Charge subscribers based on their volume of usage of high-bandwidth applications
- Charge extra for QoS guarantees
- Limit app usage while a user is roaming
- Lower the bandwidth of wireless subscribers using heavy-bandwidth apps during peak usage times.

A Simplified Data Flow with 4G…(1/2)



Reference :
TS 29.281
TS 23.401
TS 29.274

A Simplified Data Flow with 4G… (2/2)



Reference :
TS 29.281
TS 23.401
TS 29.274

Outline

- Brief history of wireless
- What is wireless communication?
- Bottom-down approach
  - Physical layer : how can we transmit signals in air?
  - Link layer : multiple access
  - Wireless impact higher layers?
- Wireless Systems
  - Mobile Broadband Networks
  - Wifi
  - Sensor Networks, Adhoc Networks

IEEE 802.11 Wireless LAN

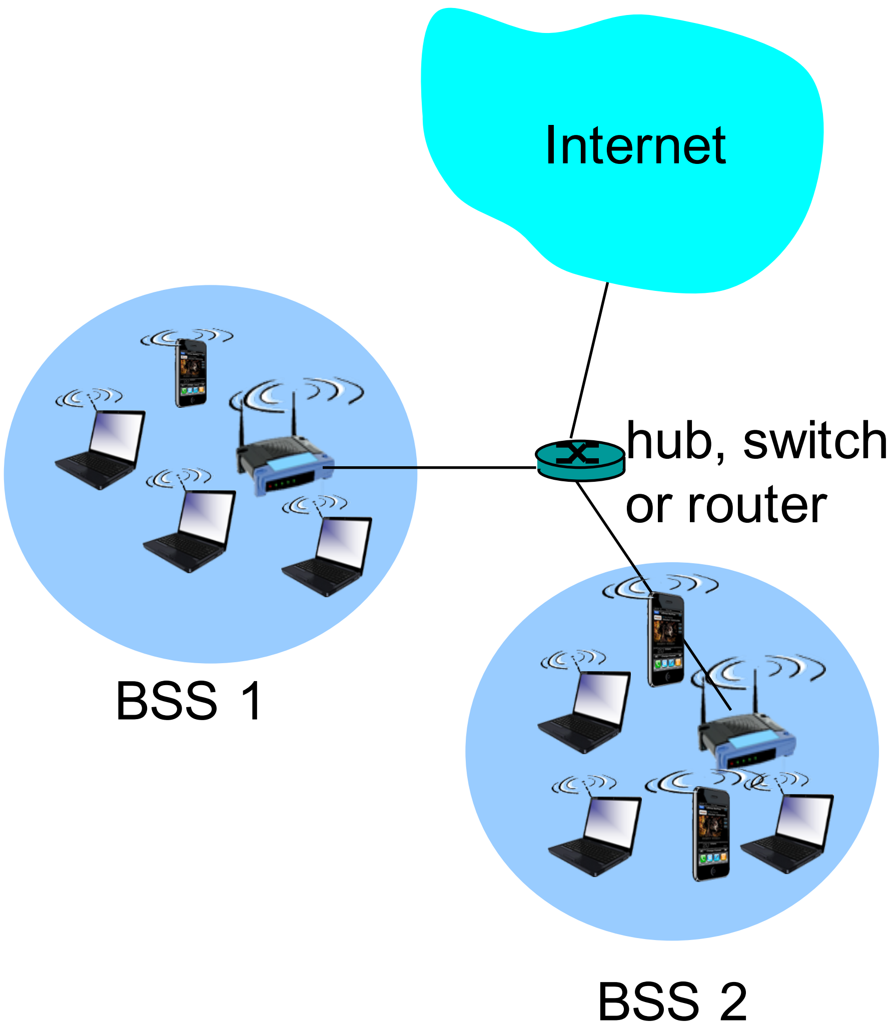
802.11b
- 2.4-5 GHz unlicensed spectrum
- up to 11 Mbps

802.11a
- 5-6 GHz range
- up to 54 Mbps

802.11g
- 2.4-5 GHz range
- up to 54 Mbps

802.11n: multiple antennas
- 2.4-5 GHz range
- up to 200 Mbps

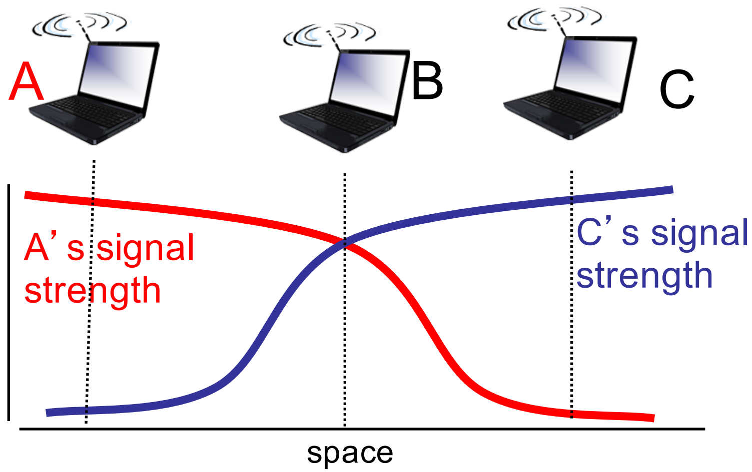
802.11 LAN architecture



- wireless host communicates with access points (AP)
- Basic Service Set (BSS) in infrastructure mode contains:
  - wireless hosts
  - access point (AP): base station
  - ad hoc mode: hosts only

Wireless network characteristics (1)

Multiple wireless senders and receivers create additional problems (beyond multiple access):

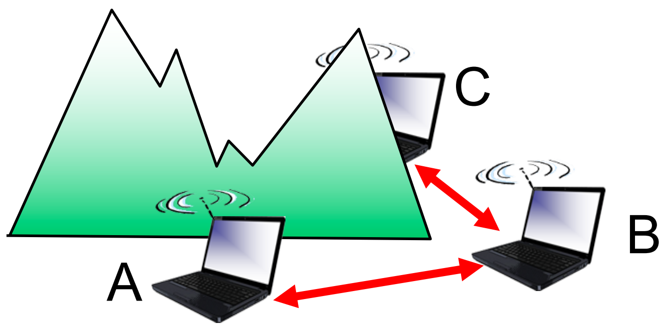


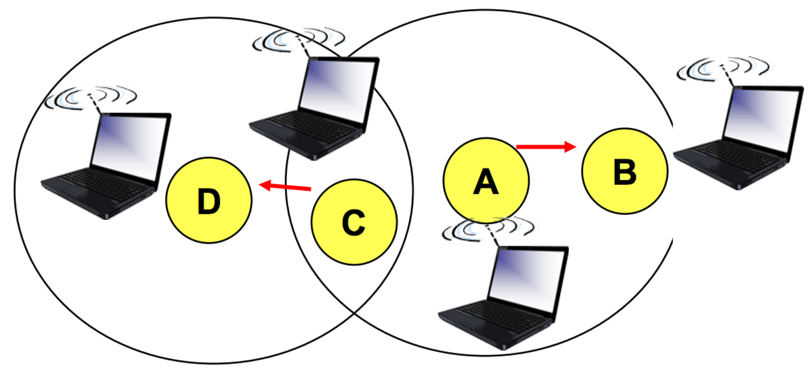
Signal attenuation:

- B, A hear each other
- B, C hear each other
- A, C can not hear each other interfering at B

Wireless network characteristics (2)

Multiple wireless senders and receivers create additional problems (beyond multiple access):





Hidden terminal problem

- B, A hear each other
- B, C hear each other
- A, C can not hear each other means A, C unaware of their interference at B

Exposed terminal problem

- C wants to send D, A wants to send B
- When A transmits to B, C waits
- But D is outside of the range of A, so the wait is unnecessary

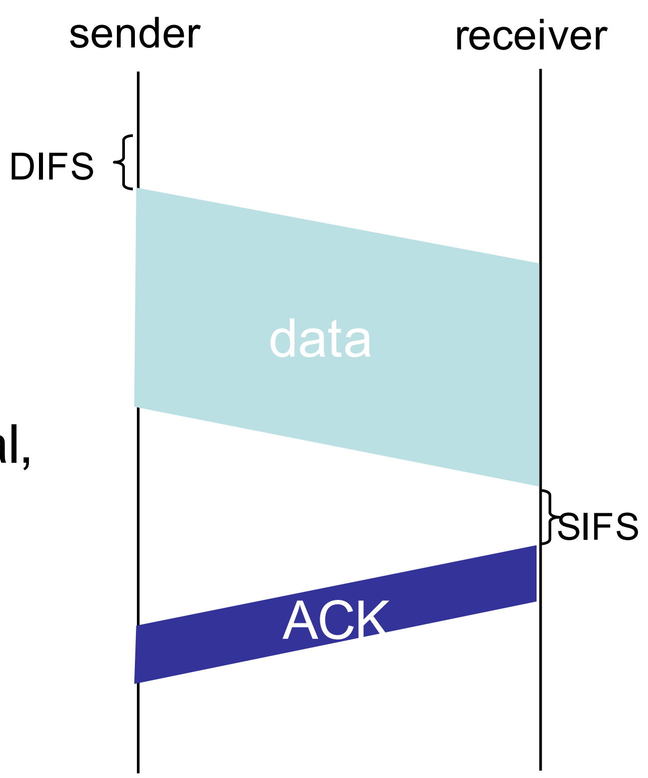
Example: IEEE 802.11 CSMA/CA

802.11 sender

- 1 if sense channel idle for **DIFS** then
  transmit entire frame (no CD)
- 2 if sense channel busy then
  start random backoff time
  timer counts down while channel idle
  transmit when timer expires
  if no ACK, increase random backoff interval, repeat 2

802.11 receiver

- if frame received OK
  return ACK after **SIFS** (ACK needed due to hidden terminal problem)



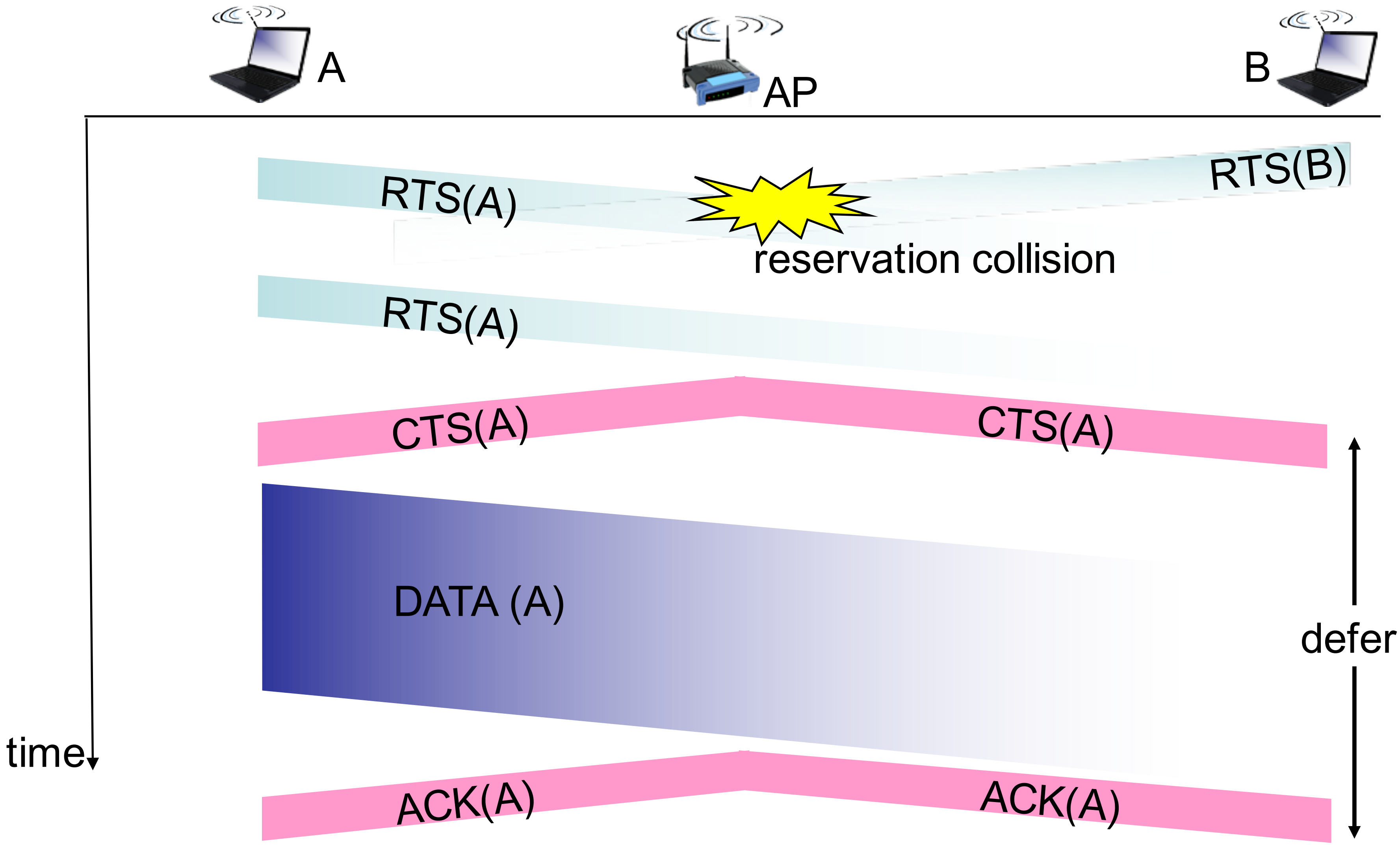
Avoiding collisions

Idea: allow sender to "reserve" channel rather than random access of data frames: avoid collisions of long data frames

- sender first transmits *small* request-to-send (RTS) packets to BS using CSMA
  - RTSs may still collide with each other (but they're short)
- BS broadcasts clear-to-send CTS in response to RTS
- CTS heard by all nodes
  - sender transmits data frame
  - other stations defer transmissions

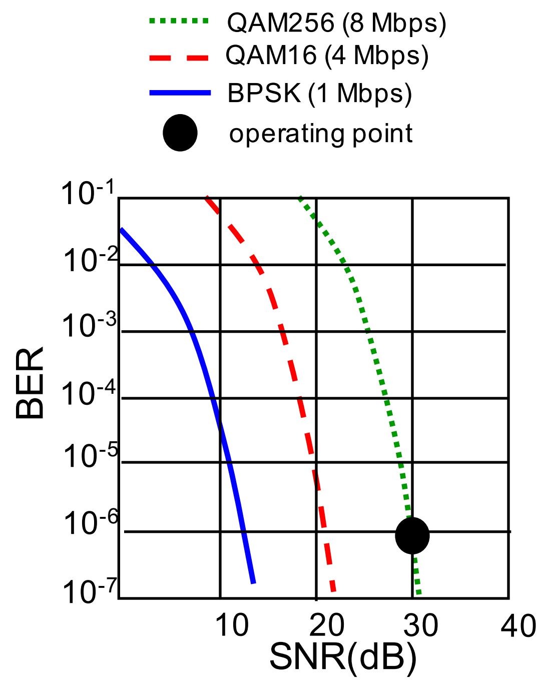
avoid data frame collisions completely using small reservation packets!

Collision Avoidance: RTS-CTS exchange



802.11 Rate Adaptation

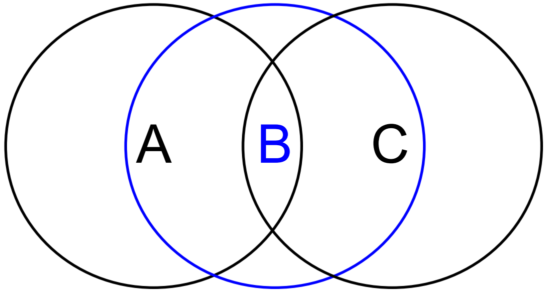
- Wireless channel characteristics: mobility, noise, interference, fading, short-term variation in channel condition (bursty bit errors)
- Rate Adaptation (RA) method left to the vendor; various schemes exist
  - based on PHY (e.g. SNR or Received Signal Strength Indication (RSSI)) or link layer metrics
  - Common: Auto-Rate Fallback (ARF) and derivatives: assumes that consecutive packet loss = probably not due to collision



1. SNR decreases, BER increase as node moves away from base station
2. When BER becomes too high, switch to lower transmission rate but with lower BER

Network coding

- Based on linear combinations of orthogonal vectors in finite fields
  - Commonly explained with XOR
- Various applications; in wireless, exploits overhearing
- Major gains claimed... but: significant overhead
  - Decoding: Inverting m x m-matrix (m = size of variable vector)
  - this needs time $O(m^3)$ and memory $O(m^2)$



A, C: hosts
B: base station

Example - goal: A => C and C => A

Without NC:
1. A => B
2. B => C (A hears this)
3. C => B
4. B => A (C hears this)

With NC:
1. A => B
2. C => B
3. B broadcasts A's msg. XOR C's msg.

Outline

- Brief history of wireless
- What is wireless communication?
- Bottom-down approach
  - Physical layer : how can we transmit signals in air?
  - Link layer : multiple access
  - Wireless impact higher layers?
- Wireless Systems
  - Mobile Broadband Networks
  - Wifi
  - Sensor Networks, Adhoc Networks

Wireless Sensor Networks (WSNs)

- Based on 802.15.4
  - Some devices: ZigBee (802.15.4 PHY+MAC + layers 3 / 7)
  - uses CSMA/CA
  - Many devices can run TinyOS or Contiki OSes

- Specific scenarios – alarm based systems, regular measurements, ... => specific improvements possible
  - e.g. static topology, regular updates: can do special routing; can put nodes to sleep when they don’t communicate
  - transport: sometimes per-hop reliability
  - often: one static sink => “funneling effect” of traffic going “up the tree”, earlier battery depletion of nodes near the sink
  - Solution: mobile sink (e.g. radio controlled helicopter)

Mobile Ad Hoc Networks (MANETs)

- Mobile devices, also acting as routers
- Memory and CPU restrictions
- Flexible environment, changing topology
- Not too many realistic usage scenarios
  - When do you not have a base station but want to connect anyway?
    - Military battlefield was a common example scenario – is it the only real use case?
  - Better to incorporate base stations and consider the (somewhat less mobile) network formed by the heterogeneous equipment connected in this way
    - Wireless Mesh Network (WMN)

Cognitive Radio

- Spectrum utilization depends strongly on time and place
  - Could do better than always use the same allocated frequencies
- Idea: let unlicensed ("secondary") users access licensed bands without interfering with licensed ("primary") users
  - Ideally, access a database which maintains a common view of who uses which spectrum
  - Many issues (e.g. security, incentives for cooperating, ..)